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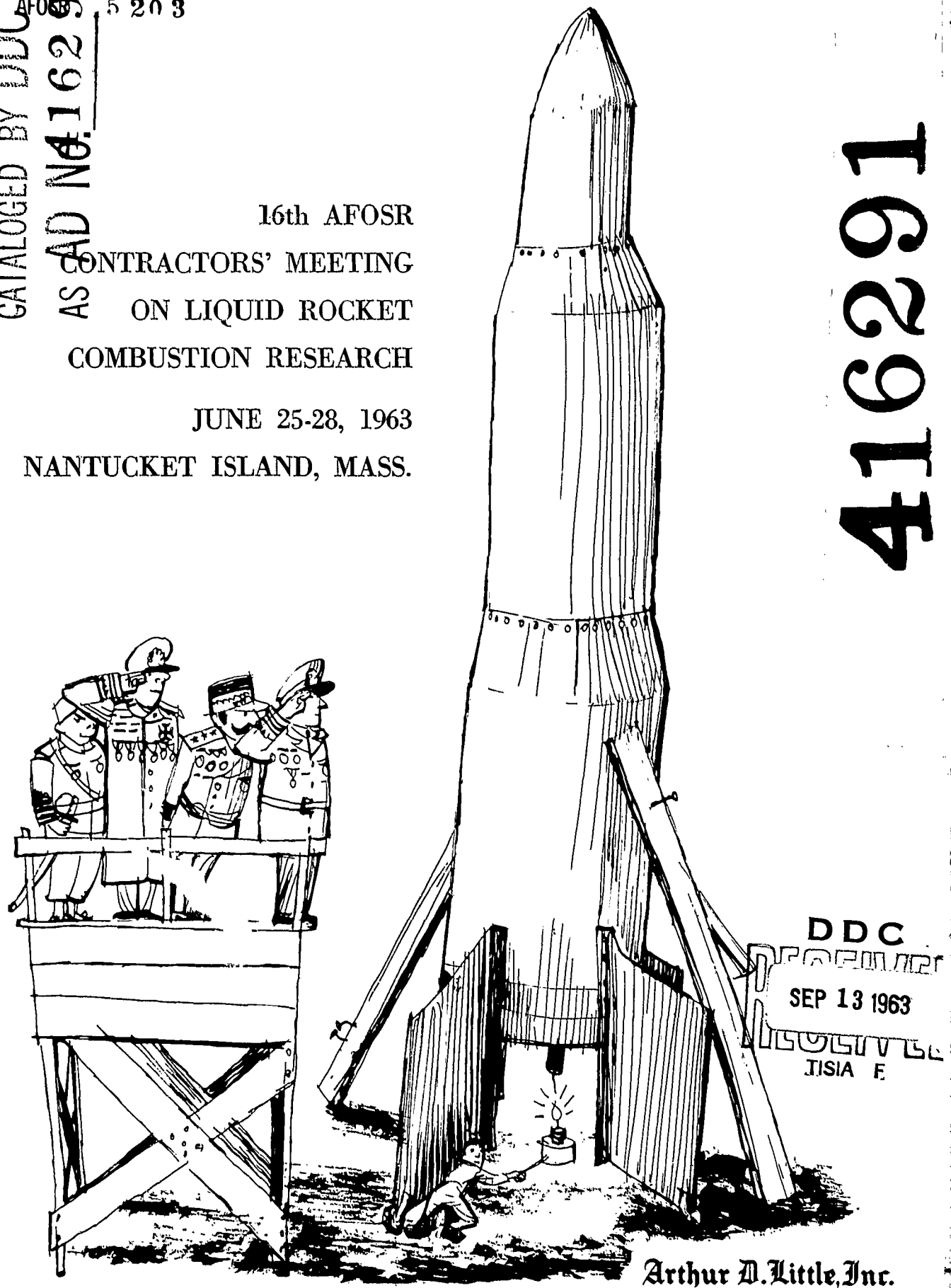
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16th AFOSR
CONTRACTORS' MEETING
ON LIQUID ROCKET
COMBUSTION RESEARCH
JUNE 25-28, 1963
NANTUCKET ISLAND, MASS.

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Arthur D. Little, Inc.

ABSTRACTS OF PAPERS

16TH AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

CONTRACTORS' MEETING ON

LIQUID ROCKET COMBUSTION RESEARCH

June 25 - 28, 1963

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COMBUSTION INSTABILITY IN SOLID PROPELLANTS

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A number of interesting experimental and theoretical developments have taken place in the field of Solid Propellants Combustion Instability in the three years since the inception of a coordinated research effort in 1960. A Summary of some of the work currently in progress will be presented.

COMBUSTION PROCESSES IN ROCKET MOTORS

L. Crocco, I. Glassman and M. J. Webb

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Previous theoretical and experimental work in the study of pre-mixed gas rocket longitudinal combustion instability had shown good qualitative agreement but poor quantitative agreement. This theory was based upon a mechanism of oscillating heat transfer to the injector and dependent upon the oscillating pressure. Variations of the injector surface temperature and also the incoming unburned gas temperature, resulted in changes in the heat transfer rate due to changes in the temperature difference between the burned gases and injector face. However, for such a coupling to be responsible for the oscillations observed, heat transfer rates much above those considered possible were required. Because of the difficulty in estimating these heat transfer rates, several experiments were devised to substantially change them and to observe the corresponding changes in the stability limits.

Other models for combustion instability were also under consideration. One of these models assumed a mass release from a short combustion zone instantaneously sensitive to the thermodynamic conditions even under high frequency oscillatory conditions. Thus no time-lag concept is employed. A periodic solution for longitudinal oscillations with shock waves in a combustion chamber, long compared with the length of the combustion zone, has been obtained. A most interesting conclusion from this theory is that there is a definite relation between the pressure wave profile and the form of the mass release rate law assumed for the analysis.

The essentials of this latter theory will be presented. Experimental results will be discussed with reference to the two theories.

MECHANISMS OF COMBUSTION INSTABILITY

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The main objective of this research program is to study the triggering mechanisms which lead to the onset of acoustic oscillations in a combustor and the interactions of these acoustic oscillations with the triggering mechanisms.

One phase of this program is devoted to the study of the basic mechanism causing self-sustained oscillations of a diffusion flame around a simulated fuel droplet in a natural-convective flow. The oscillations observed are characterized by periodic lengthening of the flame, necking in the region below the flame tip and subsequent separation of the flame tip from the main flame surrounding the simulated fuel droplet. The characteristics of the induced oscillating flow have been examined by means of hot-wire anemometers, thermocouples, schlieren motion pictures and particle-track photographs. The results obtained indicate strongly that the onset of the self-sustained flame oscillations is due to the instability of travelling Tollmien-Schlichting waves - the same mechanism which leads to the transition from laminar to turbulent flows. This same mechanism has also been found in an earlier study to be responsible for the self-sustained oscillations of a premixed flame in a forced-convective flow of a combustible mixture over a heated surface. A paper containing the main results of these two studies was presented at the AIAA Summer Meeting in Los Angeles, June 17-20, 1963.

Further study of the validity of the mechanism of self-sustained oscillations postulated above has been conducted by investigating the effects of the presence of screens and wires in the neighborhood of the simulated droplet. For some configurations, the oscillation characteristics of the induced flow are changed in phase relationships (though not in frequency), while for other configurations, the flame oscillations can be eliminated. Work is still in progress to study these effects in detail.

Another phase of the research program is concerned with the triggering of acoustic oscillations in an organ pipe due to the presence of an oscillating flame therein and with the interactions of the acoustic oscillations on flame oscillations and the flow field. Tests were conducted with and without acoustic excitations from a loud-speaker placed beneath the vertical organ pipe. Conclusive experimental evidence has been found to confirm the early conceptual model which suggests the possibility of the triggering of high-frequency acoustic oscillations by the low-frequency self-sustained flame oscillations. It has also been observed that, under some flow conditions, the energy transport between acoustic and flame oscillations can be decoupled, thus indicating the possibility of finding an engineering solution to eliminate unstable combustion due to such couplings. Work is still in progress to study the details of these energy transport processes.

HIGH-FREQUENCY COMBUSTION INSTABILITY AND SEALING OF LIQUID PROPELLANT ROCKET MOTORS

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Two concepts are being pursued in this investigation which will lead to useful design and scaling parameters for stable combustion in rocket motors. The first concept is concerned with the wave slope-velocity gradient ratio. The wave slope is that of a pressure wave propagating in a rocket chamber, while the velocity gradient is that of the gases flowing through the chamber. This parameter is suggested from the role assumed by the velocity gradient in deforming wave shapes. Thus, wave steepening or broadening, and wave amplification or attenuation can occur.

The second concept is concerned with the wave residence time as compared to the significant relaxation time that occurs in an element of volume in the rocket chamber. This parameter was suggested by some experiments on velocity-of-sound measurements in reacting gases performed by the author. Thus, with long period waves, energy-mass coupling may occur with the evaporation rate of the propellants, whereas for short period waves, energy-mass coupling may occur with the chemical or combustion rate. The investigation is both theoretical and experimental.

OBSERVATION AND ANALYSIS OF COMBUSTION PROCESSES DURING
STEADY-STATE ROCKET OPERATION WITH LOX/GH₂ PROPELLANTS

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Rocketdyne

A Division of North American Aviation, Inc.

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Experiments have been performed with a transparent-walled, two-dimensional rocket combustion chamber using liquid oxygen and gaseous hydrogen propellants. Quantitative data obtained have been used in formulating physically realistic mathematical models of rocket combustion for the particular injector types employed. Data have been obtained during operation with three injector types (viz., coaxial jets, unlike triplets, and oxidizer doublet/showerhead fuel) and a range of hydrogen injection temperatures. The data consist of: (1) oxygen jet and spray geometric relationships, obtained by high-speed motion photography; (2) combustion element velocity profiles, obtained by streak photography; (3) pressure measurements along the combustion chamber length; and (4) propellant flow rates and injection parameters.

The experimental data have led to formulation of two combustion models. One is a modification of an earlier model for LOX/RP-1 spray combustion. Here the sprays are considered to be formed in the presence of hot combustion product gases so that individual spray elements may be intimately surrounded by a reaction (combustion) front continuously from their formation to their complete consumption. This model is supported by data from the oxidizer doublet/fuel showerhead injector. The other model is a unique departure from earlier spray combustion models. The coaxial jet and triplet injector data strongly suggest the presence of a standing flame-front at an appreciable distance from the injector, so this combustion model has been formulated in terms of oxygen spray formation and hydrogen stream expansion in the absence of combustion followed by their passage through a stationary flame-front. An attempt to account for turbulent mixing of coaxial, unlike combustion gas streams has been included in this model.

Oxidizer jet disintegration by amplification and stripping of small surface waves is considered to occur. The approach by Mayer (ARS Journal, v. 31, No. 12, Dec. 1961) has been modified and extended to include a rate of surface disintegration. Experiments have been performed with single drops of RP-1 in a shock tube in attempts to determine empirically the values of atomization constants in the analysis.

INSTABILITY CALCULATIONS - INCLUDING VARIABLE ATOMIZATION,
MASS ACCUMULATION AND INJECTION

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Additional calculations have been performed to determine the regions of combustion instability with a nonlinear theory. New models to determine the local burning rate included burning rate controlled by: (1) the atomization rate; and (2) vaporization rate with varying quantities of unburned propellant in the combustor and varying injection rates. These results show that a larger disturbance is required to excite instability with an atomization model than a vaporization model and that as the quantity of unburned propellant in the combustor decreases, the combustor is more stable. The influence of injection pressure drop on stability is dependent on the combustor, in some cases improving stability and in others producing more instability.

Preliminary results of calculations considering the combustor to be a slab with a very small axial length have shown reasonable agreement with previous results obtained with the annular section.

Other projects will be briefly described and will include a short movie of screaming in an H_2-O_2 engine to show the comparison between calculated and experimental results.

EXPERIMENTAL MEASUREMENTS DURING RESONANT COMBUSTION -

A REVIEW OF JPL EXPERIENCE

J. H. Rupe

Jet Propulsion Laboratory

Pasadena, California

Simultaneous measurements of the pressure variation associated with several different locations on a chamber boundary during resonant combustion will be presented. It is intended that these data together with supplementary information on local heat transfer rates, chamber erosion, and the influence of baffles in attenuating the disturbance will serve to substantiate the postulate that the disturbance has the characteristics of a detonation wave, and under appropriate conditions can be sustained as such by a "quasi-steady" injection scheme.

A brief description of the apparatus and instrumentation will be included and JPL's intended effort in this discipline will be outlined.

ROCKET COMBUSTION INSTABILITY

Aubrey C. Tobey

Arthur D. Little, Inc.

Cambridge, Massachusetts

Considerable interest exists in reaching a comprehensive understanding of the mechanism by which harmful oscillations are excited within a rocket chamber. Past investigations demonstrate the importance of definitive knowledge of occurrences near the injector face of the rocket combustor. The objective of the program we are conducting under Contract No. AF 49(638)-1120 is to provide analytical and experimental information concerning the flame-piloting mechanism and the effect of external disturbances on its characteristics. The thesis is that in a stable system, the recirculating gases provide energy for continuous reaction of the mixture, and energy imbalance, as caused by small perturbations, creates ignition time lag changes which in turn creates changes in over-all reaction rates and fluid flow in the chamber leading to instability. Our basic attack on the problem consists of forcing a stably operating motor towards instability by inert gas injection into the recirculation zone, the primary influence being a gradual reduction of available energy in the zone with consequent changes in the over-all performance of the combustor.

Experimental work has been conducted with the use of a 100-lb rocket thrust chamber fed with gaseous methane and oxygen through axi-symmetrical co-axial jets of 0° and 30° convergence. Inert gas was injected through a peripheral ring of sintered metal located next to the injector face. The chamber has been probed for determination of local concentrations and longitudinal and radial gradients as affected by injector geometry, inert gas injection and chamber length. Thus far, instabilities attributable to inert gas injection have not been observed. No unusual trends are apparent in the concentration measurements as indicated by mass spectroscopy analyses. The validity of a conceptual model composed of well-stirred and plug-flow reactors for predicting the behavior of the rocket combustion chamber remains to be demonstrated.

Upon satisfactory completion of the gas-fed rocket study, the program will continue with examination of gaseous-liquid and finally liquid-liquid (bi-propellant) rocket studies.

COMBUSTION INSTABILITY IN LIQUID ROCKET MOTORS

L. Crocco and D. T. Harrje

Princeton University

Princeton, New Jersey

Continued studies are being made on the determination of the influential rocket parameters from the standpoint of initiating nonlinear (or "triggered") combustion instability. Some of the parameters under study which have been proven important and which will be discussed include: spacing between fuel and oxidizer elements, injection element orientation, chamber pressure level, direction and magnitude of pulse disturbance and propellant characteristics. The underlying principle governing much of the observed behavior is the displacement effect which involves the movement of the more highly vaporized propellant with regard to the droplets of the other.

Basic experiments are clarifying the distance that the vapor moves, where the vapor is generated and how this vapor generation can be influenced. Theoretical predictions of how the vapor is distributed from like-on-like spray elements with various orientations and radial locations are also being made. The third aspect of these injector studies involves refinement of the light-scattering technique to determine instantaneous droplet sizes under both steady and oscillating conditions. Certain aspects of these studies will be discussed.

Theoretical research under the linear approximation is yielding information concerning mechanisms of combustion instability. These studies deal with the detailed "microscopic" processes taking place within a rocket chamber. They are carried out by a fully time-dependent theory in order that correct phasing may be taken into account. The mechanism found to hold the most promise has been the unsteady burning of liquid fuel droplets in an oxidizing atmosphere. This mechanism provides not only the proper phasing and magnitude of response to "drive" instability but operates in the frequency range in which engines are known to go unstable. The development of unsteady compressible boundary layer theory concerning burning droplets will be discussed as it applies to the unsteady theory of the rocket engine.

COMBUSTION INSTABILITY IN GASEOUS

BI-PROPELLANT ROCKET MOTORS

M. J. Zucrow and J. R. Osborn

Purdue University

Lafayette, Indiana

An investigation is being conducted to determine the effects of the mixing of separately injected gaseous propellants on combustion oscillations in rocket motors. In these experiments, three different propellant combinations and two motors of different chamber geometries were employed. In addition, two basic types of injection systems, "showerhead" and "impinging streams", were employed.

It was determined that the injection variables exerted the predominant influence on the combustion instability characteristics of the rocket motors. The important injection variables were:

- (1) the magnitude of the injection velocity,
- (2) the relative magnitudes of the injection velocities of the fuel and air streams,
- (3) the degree of impingement of the streams,
- (4) the orientation of the injector elements, and
- (5) the spatial distribution of injector elements on the face of the injector.

It was further determined that with some mixing induced by the injector (impinging streams), the amplitudes of the pressure oscillations were related to the reactivities of the propellant combinations. With no injector-induced mixing ("showerhead"), the least reactive propellant combination was unstable while the more reactive propellant combinations were stable. For both modes of injection, it was determined that the amplitudes of oscillation diminished as chamber length increased.

An attempt is being made to correlate the instability results of these experiments using dimensionless similarity parameters that describe the driving forces, the damping forces, and the injection parameters.

INVESTIGATIONS INTO VARIOUS ASPECTS OF HIGH-FREQUENCY
COMBUSTION INSTABILITY IN LIQUID-FUEL ROCKET ENGINES

L. Crane, S. Birch and P. D. McCormack

University of Dublin

Dublin, Ireland

The work being done is based on a dynamical model of the unstable combustion system, which is considered as being subjected to pulses of energy. These pulses are at a constant frequency and are physically associated with waves of synchronized drops (in position and size) being injected into the chamber.

Synchronization of injector action is postulated as being the key to the initiating mechanism for all kinds of liquid engine combustion instability. Such synchronization can be caused by severe vibration of the plate. This vibration stems from structure resonance to the engine noise field.

An experimental investigation into the effect of mechanical vibration of high frequency on the break-up of liquid jets is being carried out. Results so far indicate that such vibration produces over certain frequency ranges,

- a) rigid inter-drop distances
- b) uniform drop sizes
- c) synchronization of break-up from adjacent injectors.

Considerable theoretical consideration is being given to this effect also, as it is felt that this is the source of the combustion instability.

The main difference between the tangential and other modes, as far as consequences are concerned, is that this mode causes engine wall burn-out. Work on this has revealed that this is linked with the setting up of vortex patterns in the boundary layer on the chamber wall. This leads to a substantial increase in heat flux to the wall, and moreover this flux varies at high frequency.

The report will therefore be presented in five parts:

1. Notes on Rocket Engine Noise and Structure Response.

2. Effect of Mechanical Vibration of the Injector on Liquid Jet Break-up - Injector Synchronization.
3. Combustion Instability Model.
4. The Tangential Mode and Wall Burn-Out.
5. Summary of Work Done So Far, Conclusions and Future Work.

WAVE PROPAGATION AND DROPLET MOTION

IN OSCILLATORY COMBUSTION

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A model for evaluating the driving and damping forces for combustion oscillations has been developed in terms of the motions of liquid droplets with respect to a relatively weak wave resulting from some initial disturbance.

The mathematical formulation for the changes in an initial droplet distribution with time have been formulated for a one-dimensional model for steady state and oscillating conditions. These equations relate the heat release to the driving force on the basis of the spatial location of the droplets with respect to the wave. The set of equations necessary to obtain numerical solutions is unfortunately complicated and numerical methods must be used. Even these are difficult because of the appearance of triple integrals for the oscillating solutions. Simplifications have been made which will permit obtaining numerical solutions. These calculations are now in progress.

A simplified model treating the spray as a continuum and determining the effects of an acoustic wave on droplet density distribution has resulted in the following observations:

1. The density fluctuations are maximum at the velocity nodes and zero at the loops. This results in part from the fact that particles initially at the velocity nodes tend to remain there while other particles periodically enter and leave the nodal position from both directions.
2. The fluctuations in droplet density are out of phase with the velocity fluctuation. The phase difference depends on droplet radius and mass as well as oscillation frequency.

THE FEASIBILITY OF A ROTATING DETONATION

WAVE ROCKET MOTOR*

J. A. Nicholls and R. E. Cullen

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The possibility and feasibility of using detonative rather than deflagrative type of combustion in a rocket motor is considered. Partial motivation for this consideration lies in the possibility of circumventing the combustion instability problem. That is, the extreme form of an instability would be utilized deliberately and thus designed for if possible. Other advantages may include geometrical flexibility of engine design, possibly a smaller motor per unit thrust, and expected ease in designing successful large motors once the fundamental processes are understood. A pertinent question is whether the detonation engine will realize as high a specific impulse as the conventional motor.

The critical problems that would have to be faced in determining feasibility of such an engine would include high heat-transfer rates, the performance of such an engine relative to the conventional rocket, geometrical affects, and the possibility of steady detonation in a heterogeneous system.

Towards this end, experiments and analysis are described which treat these individual problems. The results of a simplified theoretical analysis of the heat transfer to the wall from a series of detonation waves are presented. The gas dynamic equations describing a gaseous detonation wave traversing an unwrapped annulus wherein fresh charge is continuously introduced and burned gases continuously exhausted through a nozzle have been programmed on an IBM 7090 computer. The results of this program reveal pressure, velocity, geometrical, and performance characteristics. The results of preliminary experiments of a detonation wave breaking up liquid drops are presented. Some preliminary results of experiments on a small rotating detonation wave motor are also reported. Finally some experimentally determined values of the detonation velocity of hydrogen-oxygen mixtures at initial temperatures down to 112°K and initial pressures up to 15 atmospheres are reported.

*The studies reported here were conducted under Air Force contract AF 04(611)-8503 with the Space Systems Division, Edwards Air Force Base, California, Air Force Systems Command, United States Air Force. The Project Engineer is Mr. R. Weiss (DGRR). The support of this agency is gratefully acknowledged.

COMBUSTION INSTABILITY RESEARCH ON SOLID AND LIQUID
PROPELLANT ROCKET MOTORS AT SHEFFIELD UNIVERSITY

M. W. Thring and J. Swithenbank

University of Sheffield

Sheffield, England

Rocket motor combustion instability has been under investigation at Sheffield University for four years. Efforts have been divided into several phases: a study of the high-frequency tangential mode of oscillation in a pre-mixed gaseous fueled rocket motor; an extension to cast double-base propellants with emphasis on the chemical response of the combustible mixture to a pressure pulse and the aerodynamics of the first tangential travelling mode; and examination of an approach to obtain a cyclic detonation wave constrained to a circular path by a controlled vortex. In addition, facilities are being developed to study H_2/O_2 air scramjet and hybrid combustion systems.

The results of the pre-mixed gaseous fuelled rocket indicate that: high amplitude travelling modes produce vorticity which, if increased either artificially or spontaneously, will reduce the engine stability and the oscillation frequency; an increase of the energy of reaction decreases the stability. Instabilities have been induced by increasing the vortex strength with tangential nitrogen jets. The use of this technique for rating engines is being experimentally investigated.

Acoustic streaming, a steady component of gas flow and a second order effect of acoustic oscillations, has been studied theoretically and experimentally. This phenomenon may create a potential type vortex which can in turn trigger the first tangential travelling mode.

The results of the above studies are being translated into a practical MHD power generation system. Included in the paper is a brief discussion of the mating of a hypersonic ramjet with a rocket motor.

SIGNIFICANCE OF DETONATION RESEARCH
TO STUDIES ON COMBUSTION INSTABILITY

A. K. Oppenheim and A. J. Laderman

University of California

Berkeley, California

The progress of launch vehicle propulsion has been marked by improvements in the level of power density (as measured, say, in Mw/liter) of heat release in the gaseous medium that is used to produce specific impulse. The performance of such high power density systems depends crucially upon the success in preventing their unstable operation. The instabilities are, as a rule, manifested by the appearance of intense and destructive pressure waves. Knowledge of the mechanism by which such waves are formed represents therefore an essential requirement for a successful development of high performance propulsion systems.

The importance of detonation research to rocket technology stems from the fact that the detonation wave produces conditions resembling quite closely those prevailing in high-performance thrust chambers, so that it can serve as a convenient means for the study of their chemico-kinetic and gas-wave-dynamic processes.

In this respect the significance of detonation studies is quite universal. Of a more particular interest is the relationship between the kinetics of the combustion reaction and the dynamics of pressure waves whose formation constitutes a prominent feature of the process of heat release at a high power density level.

The paper presents first a comparison between the power density level typical of large-scale thrust chambers and that obtained in a detonation wave, and shows, in addition, the similarity in thermodynamic operating conditions of the two systems. Results of our studies of combustion waves in detonative gas mixtures are then reviewed; in particular observations of the generation of pressures by an accelerating flame and the triggering of high-frequency transverse pressure oscillations at the onset of detonation are presented. Finally the phenomenological aspects of the stability of a chemical reaction in the presence of a pressure gradient, with consideration given to the influence of the enclosure, is discussed.

FORMATION OF DETONATIONS IN FLOWING COMBUSTIBLE GASEOUS MIXTURES

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The Ohio State University

Columbus, Ohio

Design of the equipment to study the formation of detonation waves in flowing mixtures of hydrogen and oxygen has been completed and fabrication is well under way. The utilization of detonation tubes available from previous studies in the Laboratory would not allow sufficiently high linear gas velocities to be obtained without unreasonably high flow rates. Therefore, a smaller diameter tube has been substituted. Flow rates will be varied so the Mach numbers will range from 0 to approximately 0.5 during the various experiments. Flame propagation rates will be measured with ionization probes and multichannel, high-speed electronic counters. Time intervals will be measured in steps of 1 or 0.1 microsecond. Associated theoretical studies have been initiated, but the major initial effort is being expended in fabricating the necessary flow controls and detonation tube. When the experiments are initiated, more effort can be placed on the theoretical aspects.

A review will be given of previous experimental and theoretical studies at the Rocket Research Laboratory of The Ohio State University which are concerned with detonation phenomena. These investigations began in 1955. Mixtures investigated experimentally under static conditions were hydrogen-oxygen, hydrogen-oxygen-diluent (nitrogen, argon, helium, and carbon dioxide), acetylene-oxygen, acetylene-air, nitrous oxide, hydrogen-nitric oxide, carbon monoxide-oxygen, methane-oxygen, and hydrogen-nitrous oxide.